Characterization of Conduit-Matrix Interactions at the Santa Fe River Sink/Rise System, Florida

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Abstract

Investigations of the Santa Fe River Sink/Rise System in north Florida provide the opportunity to examine the interactions between a subsurface conduit system and the surrounding unconfined eogenetic karst aquifer. The conceptual fluid flow model at this site, located within O'leno State Park and River Rise State Preserve, has evolved through time as more information has been obtained. Initially, the research focus was on understanding the conduit system. Natural and introduced tracers helped to establish flow paths and velocities; these efforts were complemented by mapping by cave divers. Additional work examined the interactions between water in the conduit system and the surrounding aquifer through monitoring of discharge into and out of the conduit system, conduit and aquifer water levels, and episodic chemical sampling. Results indicate that the underground conduit system drains water from the surrounding aquifer during most time periods. Flow reverses, moving water from conduits to matrix porosity, during high discharge events in the upper Santa Fe River that raise hydraulic heads in the conduit system above those in the surrounding aquifer. This reverse flow has implications for water budgets, water quality, and dissolution of the conduit system. Recent work suggests additional complexity to the system due to both heterogeneity of hydraulic conductivity and multiple origins of water discharging from the system. Hydraulic conductivity varies by 4 orders of magnitude as determined by slug tests and responses of wells to perturbations, creating complexities of exchange between conduits and matrix. Water budget studies, monitoring, and chemical sampling suggest that water within the aquifer is provided by a single discrete input at the River Sink, local diffuse recharge, as well as a source of water upwelling from several hundred meters deep in the aquifer. The importance of each input varies greatly through time, depending on hydrological conditions. Although this work represents a single study site, it demonstrates some of the complications of heterogeneity of flow and water-rock interactions in eogenetic carbonate aquifers punctuated by conduits.

Introduction

Understanding of flow in karst aquifers has evolved in the last two decades from focus on large conduit systems to more holistic characterization of the conduits, fractures, and matrix and their interaction (White, 2002). Although large conduits and allogenic recharge such as sinking streams are the most obvious features of karst aquifers, diffuse recharge and flow through the surrounding matrix can be significant. This variety of flow paths is particularly true for eogenetic karst aquifers, which have not been deeply buried and retain high matrix permeability (e.g., Vacher and Mylroie, 2002; Florea and Vacher, 2006). In telogenetic karst aquifers, where recrystallization has formed dense rock with low matrix porosity and permeability (Vacher and Mylroie, 2002), diffuse flow and recharge may occur within fracture networks.

O'leno State Park and River Rise State Preserve in North-Central Florida host a sinking stream (the Santa River Sink), its resurgence (the River Rise), and a large conduit system. The surrounding upper Floridan Aquifer (UFA) is eogenetic and unconfined. Thus, this region provides an opportunity to examine the interactions between conduit flow and the surrounding aquifer. Research of the system has included characterization of conduit and aquifer properties, delineation of fluid inputs to the conduit, and quantification of exchange of water between conduits and the surrounding aquifer.

Study Area

This research was conducted in the Santa Fe River basin of north-central Florida (Fig. 1), which covers an area of roughly 3500 km^2 (Hunn and Slack, 1983). The basin is underlain by Oligocene and Eocene carbonate rocks that make up the Floridan aquifer system. In the northeastern portion of the basin, the Floridan aquifer system is confined by the overlying Miocene Hawthorn Group and younger undifferentiated siliciclastic sediment (Miller 1997). To the southwest, the upper Floridan aquifer is unconfined. In the study region, the UFA is about 430 m thick, unconfined at the surface, and is covered by a thin veneer of unconsolidated sands and sediments (Miller 1986). In this area, no middle confining unit exists; as a result, the UFA extends to the lower confining unit, consisting of the Cedar Key Formation (Miller 1986). Potable water extracted from the aquifer is estimated to come from the upper 100 m of the Eocene Ocala Limestone, with water becoming increasingly mineralized with depth in the aquifer (Hunn and Slack, 1983; Miller, 1986). Porosity and matrix permeability of the Ocala Limestone average about 30% and 10^{-13} m^2, respectively (Budd and Vacher, 2004; Florea and Vacher, 2006).

The study area features an approximately 5-km gap in the surface flow of the Santa Fe River where it disappears into a 36-m deep sinkhole known as the Santa Fe River Sink and ultimately reemerges at a first magnitude spring called the Santa Fe River Rise (Fig. 1) (Hisert, 1994; Martin and Dean, 2001). This study focuses on the unconfined region of the UFA between Santa Fe River Sink and Rise. Above the River Sink, the Santa Fe River basin is poorly confined to confined. The Santa Fe River water entering the aquifer at River Sink is generally comprised of runoff and water supplied by the surficial aquifer or permeable zones within the Hawthorn Group. It is generally brown and tannic, with low dissolved solids.

Shallow groundwater in the UFA is generally clear, has equilibrated with the surrounding limestone, and is characterized as Ca-HCO_3-type water (Sprinkle, 1989). In the unconfined UFA in north-central Florida, runoff is generally negligible and very little channelized surface drainage is present because the soils are permeable and the slope of the land surface is gradual to flat. Consequently, average annual aquifer recharge rates are high. Estimates range between 45 and 60 cm/yr based on water budget analyses (Grubbs 1998), or 33 to 44% of the annual average precipitation of 137 cm (Hunn and Slack, 1983).

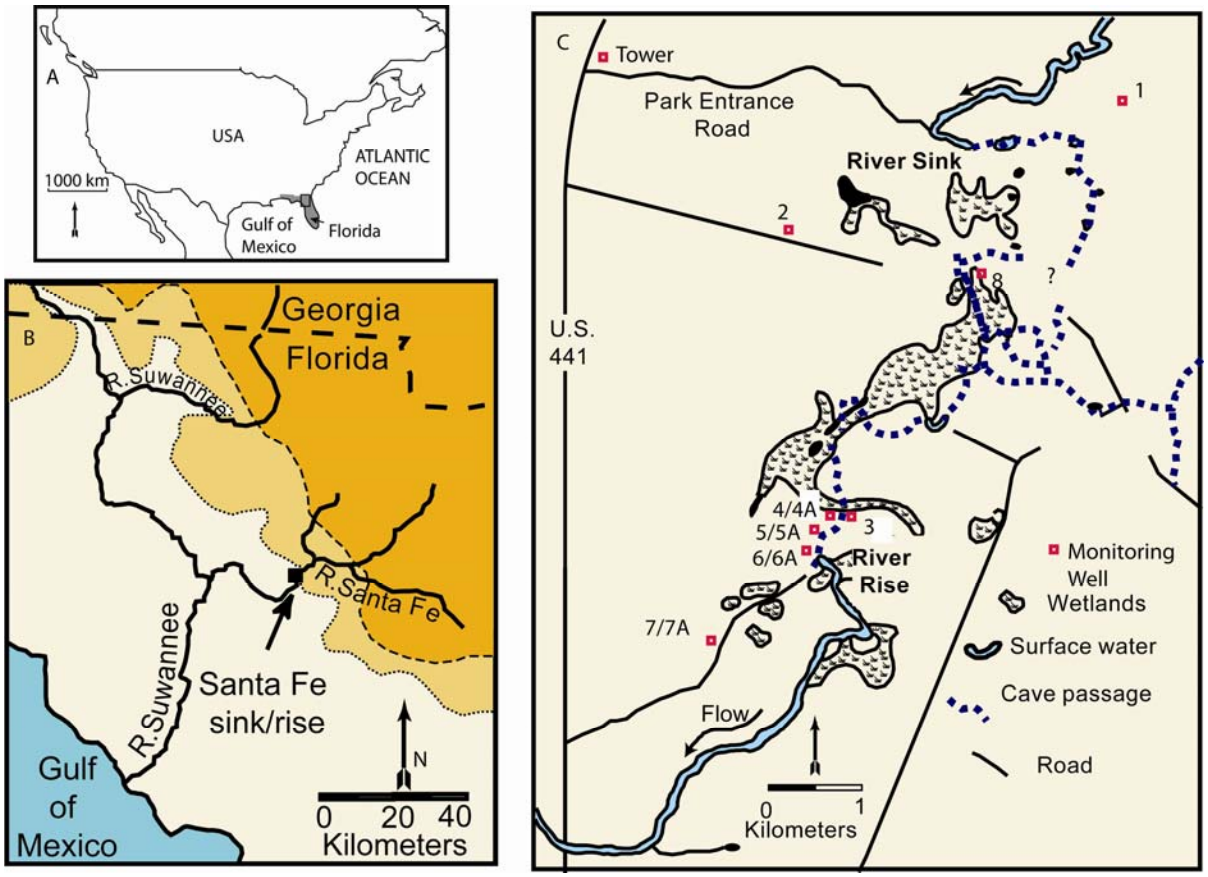

Fig. 1. Location and schematic map of the study area (modified from Ritorto et al, in press). (A) Location of Florida (shaded) within the United States. (B) General setting of the Santa Fe River Sink and River Rise. Shading indicates unconfined, poorly confined, and confined conditions of the UFA (Grubbs, 1998). The transition from unconfined to poorly confined is dotted, and the transition from poorly confined to confined is dashed. (C) Details of the study area including the locations of the Santa Fe River Sink and River Rise, monitoring wells, and mapped and inferred conduits.

Conduit System Characterization

Hisert (1994) used a gaseous tracer (SF_6) in two separate tracer tests to link the River Sink to Sweetwater Lake and Sweetwater Lake to the River Rise with velocities of several km/day. To estimate velocities at a variety of conditions, Martin and Dean (1999) and Screaton et al (2004) traced temperature signals from the River Sink, through intermediate karst windows, and through the River Rise. Estimated velocity increased with discharge into the River Sink, as determined from stage measurements (Screaton et al, 2004). Not surprisingly, these velocities and the large diameter of the conduits (~20 m) yield estimates of Reynold's number that confirm turbulent flow within the conduits.

Martin (2003) used stage measurements at the River Sink and River Rise to determine head losses through the conduit. By treating the conduits as circular pipes and combining the observed head losses, inferred velocities and conduit geometry, Martin (2003) estimated Darcy-Weisbach friction factors of 6 and 18 for the conduits. The friction factor value is an indicator of friction losses, most of which occur at a few isolated constrictions or collapses within the conduit system (Wilson, 2001). Compilation of friction factors by Jeannin (2001) suggest values ranging from 0.12 for smooth and unconstricted conduits to 24-340 for conduits with significant collapses (Atkinson, 1977). Results from the Santa Fe Sink/Rise system are intermediate, suggesting the presence of some constrictions or collapses; however, tracing of temperatures through intermediate karst windows (Screaton et al., 2004) does not reveal any significant variations in velocity along the conduit.

Fluid Inputs

At low river stage, Skirvin (1962) inferred significant groundwater contributions to the conduit system based on a change in color and water chemistry between the dark brown tannic water entering the River Sink and the clearer water discharging from the Rise. At high river stage, brown tannic water has been reported in local wells, suggesting invasion of river water. Martin and Dean (2001) observed that concentrations of conservative solutes (Cl^-, SO_4^{2-}, and Na^+) in a well located down the regional gradient from the conduits of the Santa Fe River became increasingly dilute in the months following 1998 flooding along the Santa Fe River. This dilution suggested invasion of the allogenic waters from the conduit into the surrounding aquifer.

Detailed characterization of the water chemistry at the River Sink, River Rise, and from wells within the adjacent aquifer further characterize water sources at the River Rise (Moore et al., submitted). In addition to local diffuse recharge and allogenic input, upward flow from the deep aquifer provides water and dissolved solids to the conduit system. Although the total volume of water flow could not be quantified because the deep water composition is unknown, this source of water was observed to vary inversely with the Rise stage with upwelling increasing during droughts. The upward flow also influences temperature of the ground water as shown by temperatures at Well 2 up to 4°C above that in the other wells (Fig. 1). These temperature differences suggest a vertical flow velocity of 1 m/year at the location of Well 2 and that the upward flow is heterogeneously distributed (Moore et al., submitted).

Comparison of discharge into the River Sink and out of the River Rise has allowed quantification of the gains and losses from the conduit system (Screaton et al., 2004; Martin et al., 2006; Ritorto et al., in press). The conduit system gains water between the River Sink and Rise except for short periods of elevated discharge into the River Sink (Fig. 2). At these times, the conduit system temporarily loses rather than gains water, similar to bank storage along a surface stream. Based on 5 years of observation data, Ritorto et al. (in press) estimate that only about 2% of the volume entering the conduit system at Rive Sink enters the surrounding aquifer following storm events. Thus, although the volumes of water flowing into the River Sink are large, the majority of it appears to have little interaction with the aquifer.

Hydraulic head measurements in monitoring wells near the conduits confirm that losses of water from the conduit occur as conduit heads exceed those in the surrounding aquifer; the conduit gains water when hydraulic heads in the monitoring wells are greater than those of the conduits. The relationship between volumes lost (or gained) and head gradient between conduit and aquifer appears linear (Martin et al., 2006), suggesting that the flow outside of the conduit follows Darcy's law.

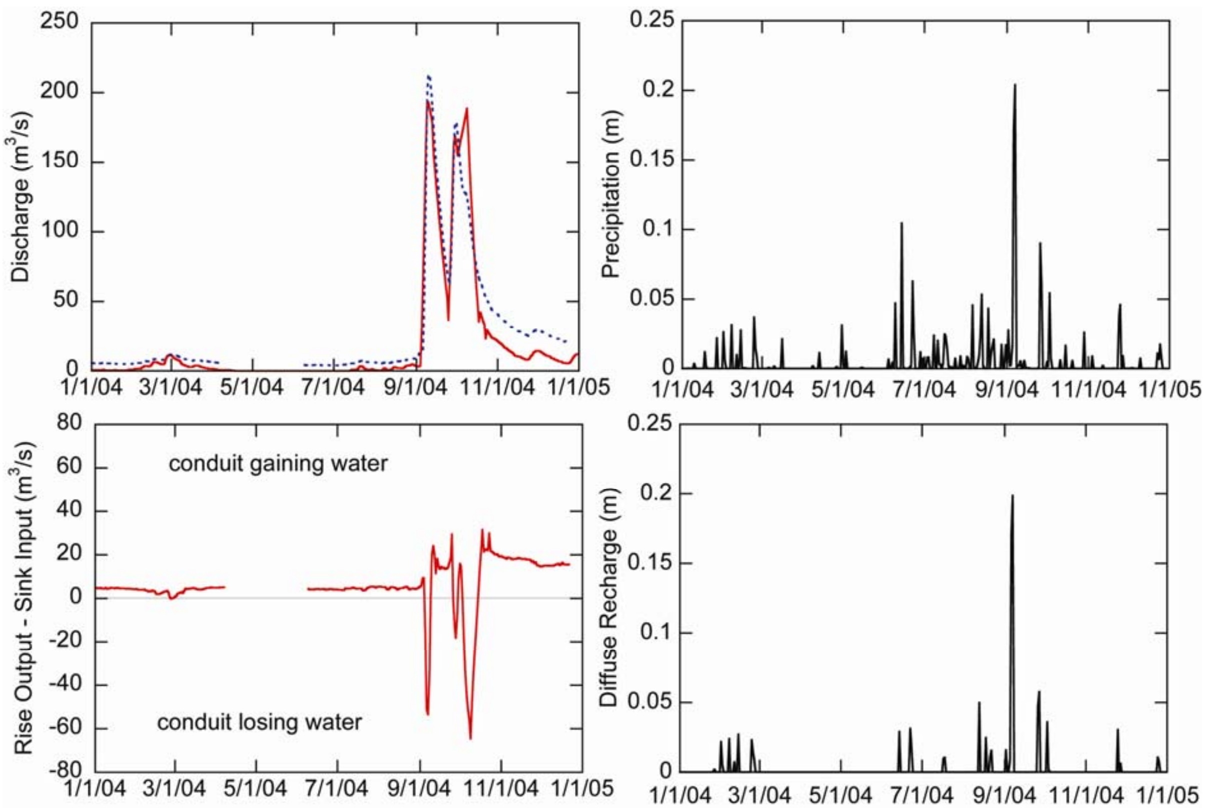

Fig. 2. 2004 discharge at River Sink (red solid line) and River Rise (blue dashed line) shown on top left. Rise output-Sink input shown on bottom left. Precipitation and estimated diffuse recharge are shown on top and bottom right, respectively.

Diffuse Recharge

The timing of diffuse recharge to the unconfined aquifer surrounding the conduit system has been examined using available precipitation data, with evapotranspiration approximated with the Penman-Monteith model (Dingman, 2006), and a daily tracking of estimated soil moisture (Ritorto et al., in press). Resulting estimates of recharge for 2002 to 2007 ranged from 17% of precipitation during a low precipitation year to >53% during the highest precipitation year, illustrating the highly variable nature of diffuse recharge in this region. Rainfall during summer thunderstorms often results in little recharge due to high evapotranspiration rates and antecedent low soil moisture (e.g., Martin and Gordon, 2000). In contrast, large events during fall and winter can provide the majority of recharge (Fig. 2). This conclusion is consistent with previous estimates based on water level changes in a north-central Florida well (Florea and Vacher, 2007).

Because exchange between the conduits and aquifer are controlled by the head gradient, volumes of fluid lost from the conduit do not scale directly with the size of the flood event. Diffuse recharge greatly impacts hydraulic heads and thus the exchange between conduits and matrix. If significant diffuse recharge precedes or accompanies high discharge into the Santa Fe River Sink, the increase in aquifer hydraulic head will reduce the losses from the conduit. In contrast, if a high discharge event on the Santa Fe occurs when the water table is extremely low, losses from the conduit will be enhanced. As a result, the distribution of recharge to the matrix porosity depends on the distribution of precipitation in the region and specifically the relative amount of precipitation on the confined and unconfined portions of the watershed.

Aquifer Heterogeneity

In addition to hydraulic gradient, water exchange between the conduits and aquifer will be controlled by aquifer hydraulic conductivity. Permeability tests on Floridan aquifer cores yield values ~10^{-13} m^2 (Budd and Vacher, 2004), or hydraulic conductivity of ~0.08 m/day. Slug tests performed on wells screened at the approximate level of the conduit yielded hydraulic conductivities ranging from 3 m/day to 6 m/day (Martin et al., 2006); wells screened just below the water table yielded hydraulic conductivity values up to 3 times higher (Myer et al., 2007).

Martin et al. (2006) used monitoring well responses to conduit head changes to estimate the transmissivity between the conduit and wells. The influence of the conduit head change was assumed to be significantly larger than that due to the diffuse recharge; thus, the influence of diffuse recharge was not considered. Resulting transmissivity values ranged from 900 to 500,000 m^2/day, with monitoring wells closest to the conduit yielding smaller values and those at greater distances yielding larger transmissivities. Assuming a thickness of 100 m of active flow in the UFA, this implies hydraulic conductivity values ranging from 9 to 500 m/day. The increase in observed hydraulic conductivity as measurement scale increased was interpreted to be a result of water flowing through preferential flow paths over longer distances, consistent with observations from other karst and fractured aquifers (Rovey and Cherkauer, 1995; Person et al., 1996).

To assess the error introduced by neglecting diffuse recharge, one dimensional numerical modeling was conducted. For analysis of water levels during storms, the head increase due to diffuse recharge and the water level rise due to propagation of the signal from the conduit will work together, and inclusion of diffuse recharge could result in a lower estimated hydraulic conductivity (Ritorto, 2007). In contrast, the addition of diffuse recharge to long term (three year) simulations resulted in higher hydraulic conductivity estimates because the water received through diffuse recharge must be able to migrate to the conduit. Despite the differences in the hydraulic conductivity analyses caused by inclusion of diffuse recharge, general patterns of observed hydraulic conductivity are consistent with conclusions drawn by Martin et al (2006). Hydraulic conductivities determined using data from the wells closest to the conduits (~100 m) are similar to slug test results and ~2 orders of magnitude greater than estimates from cores. This difference suggests that, even at the borehole scale, some preferential pathways exist that are not reflected in the core measurements. Results from wells located ~1 km or more from the mapped conduits indicate hydraulic conductivities ~2 orders of magnitude higher than those at ~100 m and 4 orders of magnitude higher than those obtained from cores, suggesting access to large dissolution features.

Summary

The underground conduit system at the Santa Fe River Sink/Rise drains water from the surrounding aquifer the majority of the time. Water in the aquifer is generally derived from diffuse recharge, which quickly equilibrates with the surrounding aquifer minerals. Variations in mineralogy with depth causes increase mineralization of the aquifer water and these variations and differences from composition of diffuse recharge provide natural tracers for flow. Estimates of diffuse recharge through time suggest high temporal variability, with little recharge provided by summer storms and large contributions coming from major storm events such as hurricanes. Mineralized fluids from the lower portion of the aquifer also provide water to River Rise, with a relative importance that increases as river stage decreases.

During high discharge events in the upper Santa Fe River, hydraulic heads in the conduit system rise above those in the surrounding aquifer. Flow reverses, moving water from the conduit to the aquifer. At these times, the aquifer is vulnerable to contamination from the introduced river water. Differences in the chemical composition of surface and aquifer water drive dissolution of the conduits. Significant heterogeneity of hydraulic conductivities is inferred for the aquifer, with four orders of magnitude variation from core to kilometer scale measurements. This heterogeneity will cause the patterns of river water invasion to be complex, with river water traveling significantly farther in high-permeability features than the surrounding matrix.

Acknowledgments

The authors acknowledge the Florida Department of Environmental Protection, O’Leno State Park and River Rise State Preserve, and the Suwannee River Water Management District for their cooperation, and Randy Dean, Brian Ginn, Abby Langston, Jennifer Martin, Paul Moore, Mike Ritorto, Brooke Sprouse, and Lauren Smith for their work on the project. The research was funded by the National Science Foundation grants EAR-9725295, EAR-003360 and EAR-0510054 and by the Florida Department of Environmental Protection Grants numbers S00060, S0141, and S0181.

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